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Aerosol measurement in Norwegian road tunnels

A background revive

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Introduction

When we first asked for dust monitors with measuring levels at 50 to 400 micrograms / m3 the intended use was for start of dust removing equipment in the Nygårdstunnel in Bergen. The producer of this equipment had convinced the local politicians that this was needed. The energy needed for this was in the size of 350kWatts. As responsible for cost we did not want to run this unnecessary. The seller had convinced other people that this kind of measurements was impossible, and the equipment should run between 8 to 10 am and 3-5pm as in several other locations.
Luckily SICK could offer an aerosol measurement based on scatterlight, but they did not now to what cross scatter area they should calibrate the VISIC 610, originally a stable fog detector

After discussions with Walter Wedberg, a scientist working at University of Bergen, and SICK it was agreed that an average cross scatter area on 1 μm^2 was a wise start. (Average cross scatter area is not the same as average particle size) Since we was of the opinion that we very rarely would need to start this cleaning unit, we asked the University of Bergen to do a parallel measuring, live in the tunnel with traffic under different conditions. This resulted in a paper (ref 2)
The accuracy was very good, far better than expected with the lower levels. No adjustment was found necessary.

Later on I advocated an installation of aerosol measurement in the Åkrafjordtunnel. This worked well.
When we had trouble with running the ventilation in the Bømlafjordtunnel, we tried first with one aerosol measurement unit. This improved the ventilation control. But it was still not good enough. Additional 3 units were installed, together wit temperature and humidity measurements outside and inside the tunnel. Everything was logged each minute. Now we had the data necessary to optimise the fan control. We could of course just have run all 96 fans, but that is too expensive. The tunnel has 96 fans, each on 20kW. 96*20kW equals 1920kW. You just don’t want to run too many.

The Bømlafjord tunnel

In western Norway we have many road traffic tunnels that are more than 500m long. The longest one is 24500m long. Most of the tunnels are one tube with bi-directional traffic.

One of these tunnels is the Bømlafjordtunnel. This is a sub sea tunnel that is 7860m long, with lowest point at 260,4m below sea level.

During the first year with traffic in the tunnel our expanses for ventilation of the tunnel was very high. On average we used 7000kWatt/hours each day. And we still had a lot of complaints caused by reduced line of sight in the tunnel. Some claimed that the reduction in sight always was caused by humidity, others that it was caused by dust/soot particles from diesel engines. *As we will see both fog and dust may be a problem.*

The number of complaints caused us to first install one dust monitor. We selected a dust monitor based on backward scatter light with measuring point outside the monitor. The monitor had been tested earlier by the University of Bergen (ref01) and found to have a very good accuracy. This monitor will not see any difference between fog and dust, but is calibrated in microgram/m3.

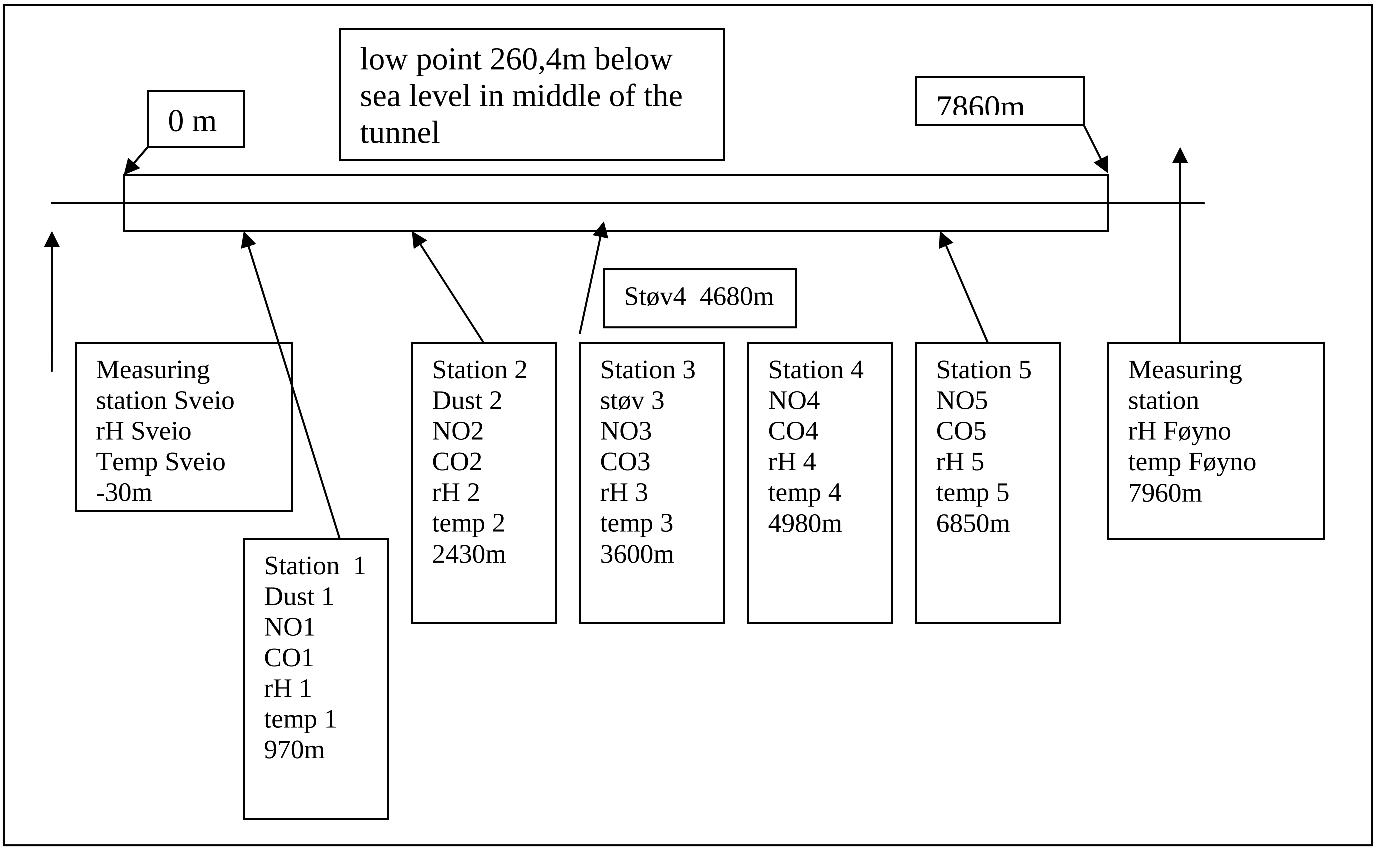
So how to see what is what.

In November 2001 we installed 7 sensors for relative humidity and temperature. We mounted 5 inside the tunnel, and one the outside at both sides of the tunnel. We also installed tree more dust monitors. From the start the tunnels was equipped with 5 CO and 5 NO monitors. The values of all monitors are logged each minute in a pc, which can be reached from the road traffic central. It is produced one log file each day, and the last 30 days are always available.

To make the analysis easy we included the number of fans running in the same log.

The main goal of the work done is to gain a cost optimazing of the ventilation when you still have acceptable air quality. (To have good air quality inside a long car tunnel is not economically possible)

SET UP



All measured values are logged once a minute. In addition is the number of jet fans running logged at the same interval.

Measuring technique

One important aspect of measuring different parameters is the physic of sensors used, and this is applied in the control system. We thereby will give a short description of the different sensors used.

Humidity:
Type: EHF 32A

Temperature:
Type: EFT-276

CO: Electrochemical cell; no integration time
Type Dräger polytron 2, tunnel version

NO: Electrochemical cell; no integration time
Type Dräger polytron 2, tunnel version

Dust or aerosols; backward scatter 60 degrees,
Average scatter cross-section 1 micrometer,
Integration time 255 seconds
Type Viscic 610

Wind speed of the tunnel: ultrasonic in line integral at 45 degrees across the traffic lane at 3,5m and 2,5m above surface.
Type

All sensors give 4-20mA signal to a PLC nearby the sensor. All PLC's are connected in an Ethernet with the log PC.

Combustion aerosols from diesel engines will have a cross section of less than 1 micrometer. This is clearly shown by David B. Kittelson (ref 1)
Since aerosols in a car tunnel will be from different sources, and the aerosol not necessary is spherical, larger cross section is to prefer for measurement of aerosol concentrations in a car tunnel. This my cause an error, which will give an aerosol concentration measured which is too high.
The chosen average scatter cross section was confirmed usable by Walter Wedberg (ref 2), and the physical principle has earlier been tested by A. Tjugum (ref 3).

Ventilation

Principle for the ventilation software:

NO and CO values starts the jet fans in 4 steps based on the given parameters. Her 4 steps are chosen since the used sensors has an uncertainty which will reduce their value in lower concentrations. The Dust monitor VISIC 610 has according to Walter Wedberg *ref2* an uncertainty on 6 percent of measured value with low concentrations. Because of this the control are here in 16 steps. The 16 steps are calculated from 4 parameters as ¼ of the difference between steps. This allows a more accurate control of the number of jet fans running.

Conclusion

1) The jet fans should be controlled by concentration of aerosol or dust, since we by the aerosol monitor has better accuracy, which will enable a possibility for running the jet fans in finer steps. This enables us to run fewer jet-fans, and thereby reduce the cost for electricity. This will cause us NO concentrations above limits for a few minutes every day I the middle of the tunnel. Such short timed peeks are not considered to be harmful. (The limit NO concentration in the middle of the tunnel is 7 ppm.) This peek will never be long, since the dust concentration soon will rise and start the jet fans. It is important to use the NO if/when the dust monitor is out of order. Today safety regulation demands that NO and CO measurements are connected with, and used in the control system.

2) It is a high probability for a further reduction of cost by reducing the number of jet fans in the first two major steps to 18 in each since 18 jet fans normally is enough to give the needed wind speed in the tunnel, which normally is between 3.0 and 3.5 m/s. This is even more so in a sub sea tunnel, where it is fire ventilation, which is the dominant factor for the number of jet fans installed

3) In future tunnels, especially when fire ventilation is the dominant factor for calculating the ventilation, it should be used as many steps as possible, or a ventilation toward a constant wind speed, given in steps by the pollution in the tunnel.

4) Parameters given for ventilation control today is based on the fact that it rarely is need of more than 24 of the jet fans. If we have a larger increase of the traffic we should adjust the parameters, especially for more than 24 jet fans running. This should be done since today the dust monitor not is allowed to start more than 24 jet fans.

5) From special events of pollution in the tunnel we have clear indications that the best adjustment to the ventilation control would be to change from static steps to a control toward a constant wind speed. Since this demands a complete redesign of the control system it will not be cost effective. But the principle will be tested in the Kolltved tunnel outside Bergen, which is 1070m long, and has a traffic of 16500 vehicles a day. *(Later experience from the Kolltvedt tunnelgives that this might only be used in longer tunnels)*

Analysis

19 November 2001 we concluded that the new sensors was running smoothly, and could be used. In this first period we removed dust sensor 2 to 4 from the control system by giving start criteria above measuring area. Dust monitor 1 is in the system. Parameters was downloaded 19 November 2001 at 09:40

parameters Period 1

Sensor	Unit	Main step 1	Main step 2	Main step 3	Main step 4
NO-1	ppm	5	8	10	13
Dust-1	µg/m3	200	1000	2000	2500
CO-1	ppm	50	100	150	200
NO-2	ppm	5	8	10	12
Dust-2	µg/m3	2000	2100	2200	2500
CO-2	ppm	25	50	75	100
NO-3	ppm	3	7	10	13
Dust-3	µg/m3	2000	2100	2200	2500
CO-3	ppm	25	50	75	100
NO-4	ppm	3	7	8	12
Dust-4	µg/m3	2000	2100	2200	2500
CO-4	ppm	25	50	75	100
NO-5	ppm	3	8	10	12
CO-5	ppm	25	100	150	200

Since a large part of the cost for ventilation is based on max effect used we started our investigations by analysis of what caused the highest number of fans to start.

Most extreme period

At 19:41 29 of November we had 42 jet fans running. Figure 1shows us the NO concentrations through the tunnel in actual time period and the number of jet fans running. We can from this figure see that it is the NO concentration that has caused the jet fans to start. For additional information we has shown the dust concentration in Figure 2, CO in Figure 3, relative humidity in Figure 4 and wind speed in the tunnel in Figure 5.
From these figures we can see that it is the NO concentration that has started a higher number of jet fans in the tunnel. The dust monitors and the CO monitors are all low in comparison with the NO monitors. Since the correlation to the dust monitor now is low we might wonder if it is an error in measuring or real. The value of NO is used for ventilation because a NO_2 sensor of needed accuracy not will work properly inside a road tunnel, at an acceptable cost. The NO values are used as a value for NO_2 based on a theory that the value of NO_2 is 10% of NO. But measurements done in city streets gives that the correlation between NO and NO_2 is a variable as shown by Kåre Kemp and Finn Palmgren I ref 4. It is also a well-known fact that it NO will react wit O_3 to NO_2. This relative amounts of NO and NO_2 is therefore depend on the ozone level, which we believe will wary inside a road traffic tunnel.

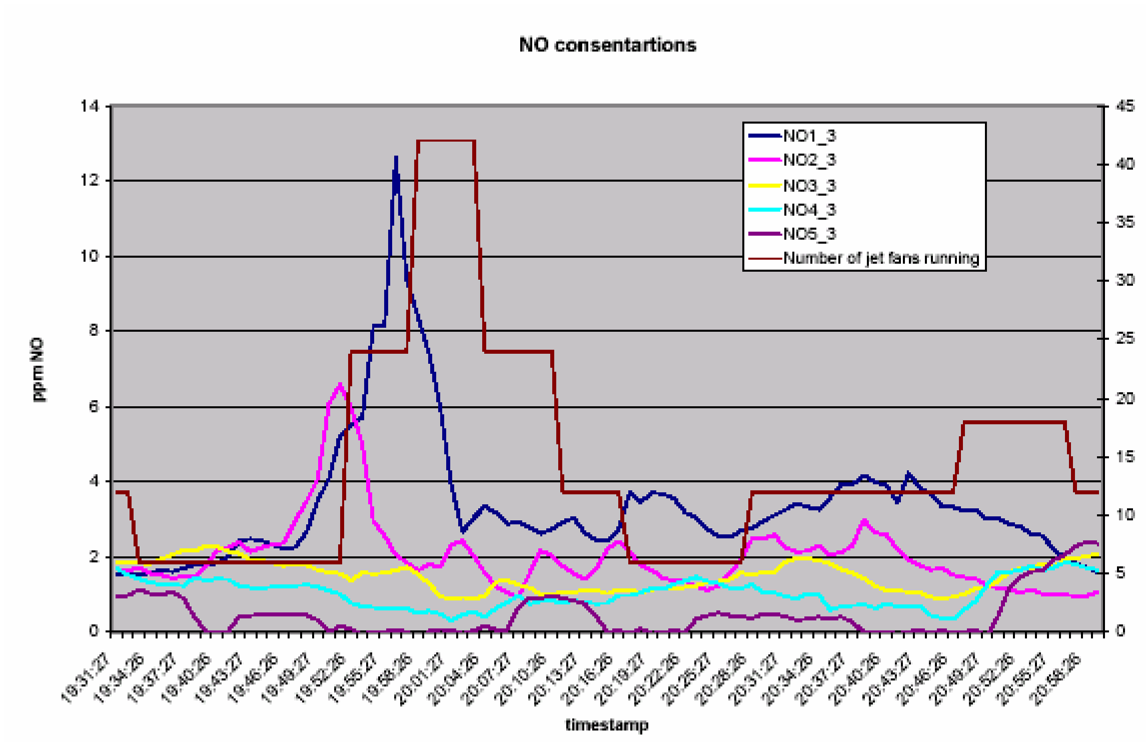


Figure 1

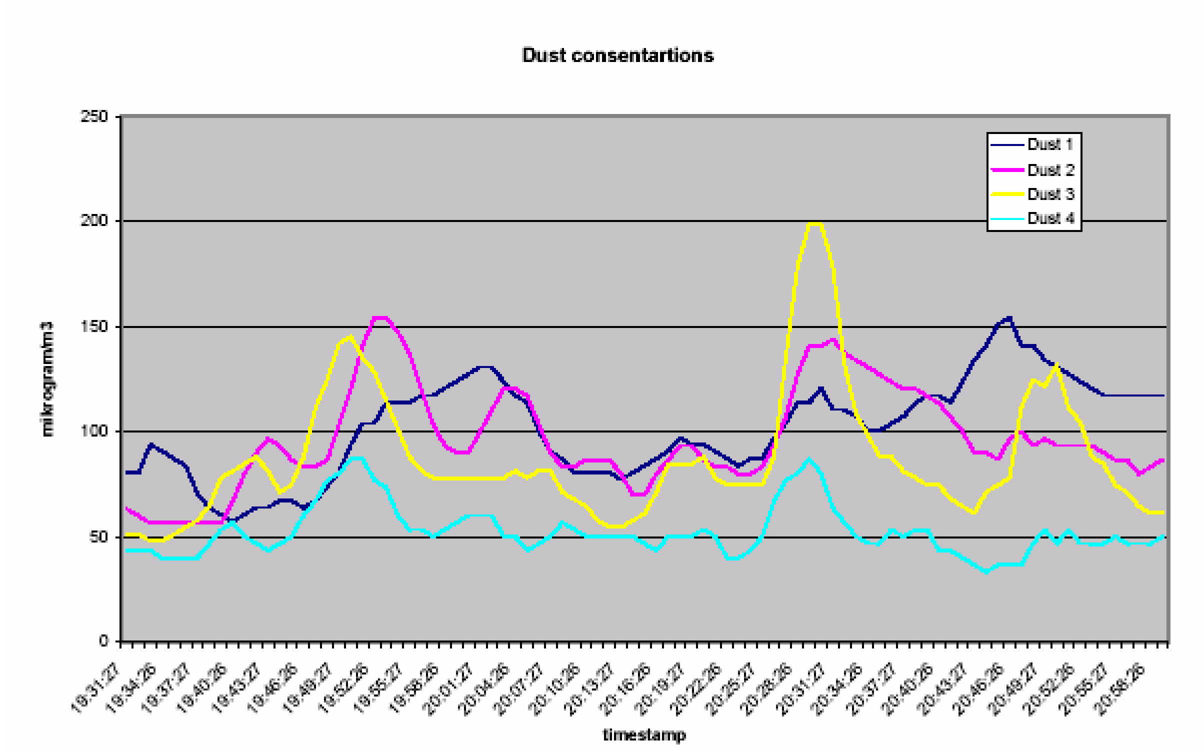


Figure 2

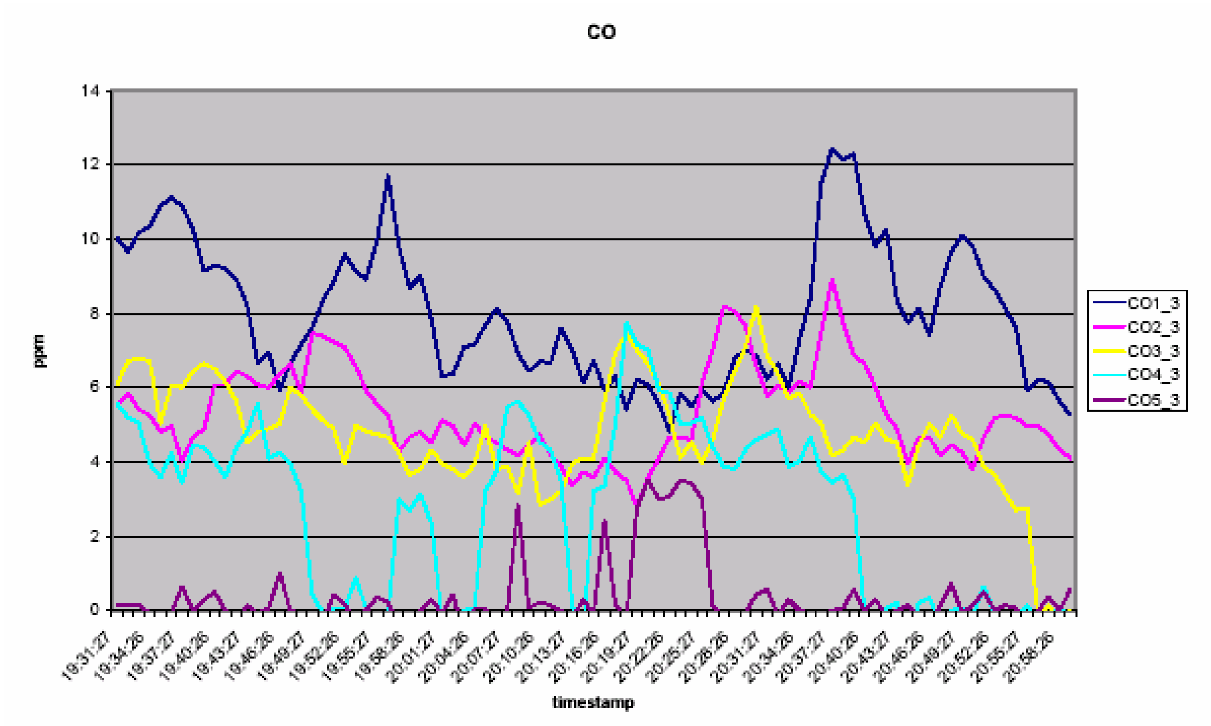


Figure 3

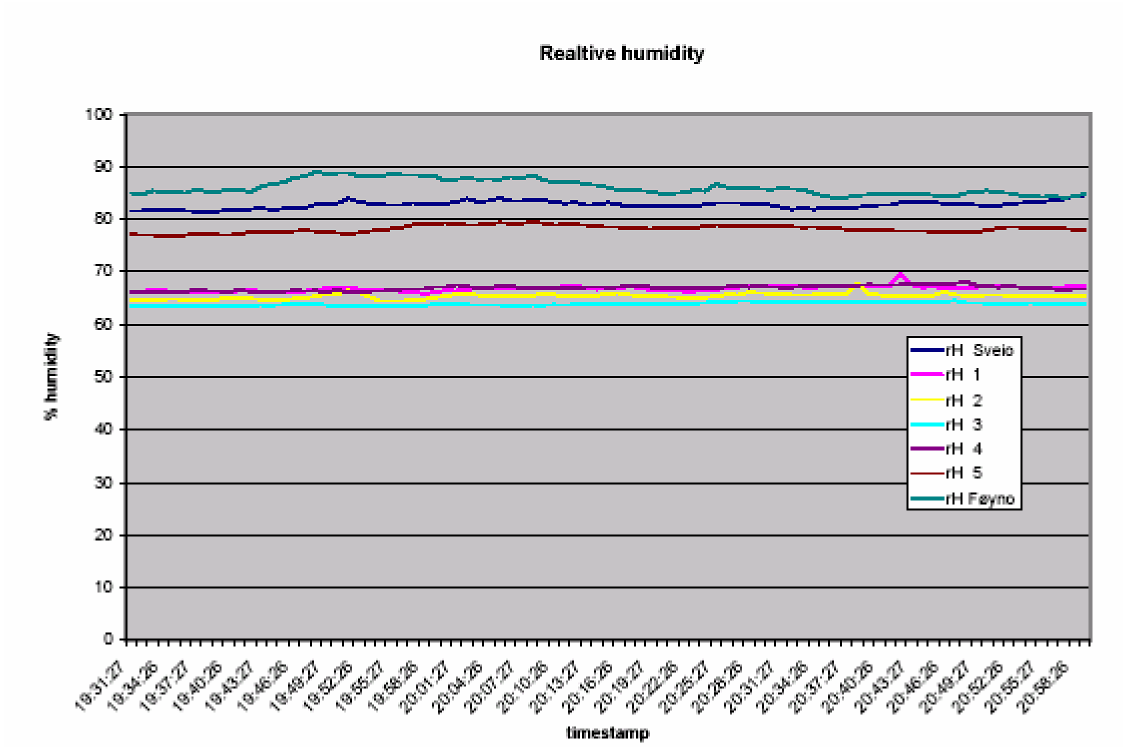


Figure 4

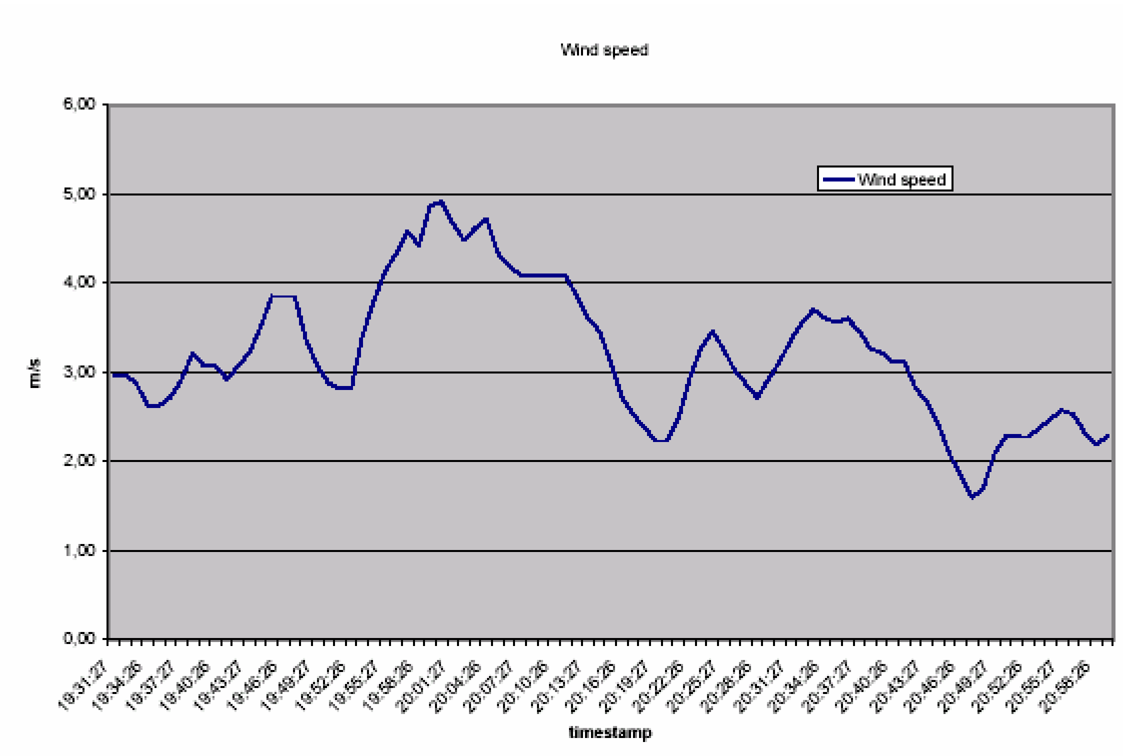


Figure 5

Analysis of general situation

23. November: 24 jet fans starts by dust monitor 1 several times. At these times we have NO levels close to starting 24 jet fans. CO levels are all low.

24. November: Highest number of jet fans started is 12. Only dust monitor can do this, but it prevents higher concentrations to occur and start of 24 jet fans.

25.November: Natural air flow of the tunnel is toward Føyno, This cause NO 5 to start the ventilation on low levels (Fire department has demanded that all ventilation is toward Sveio). This is repeated. NO3, NO4 and NO5 changes between them who it is to command start.(NO start minimum 24 jet fans)

26 November: 24 jet fans is started by dust 1 at 07:33 and ca 09:00, later on NO 3 starts 24 jet fans. Between start of 24 jet fans we are often down to 6 jet fans running, but it is mainly 12 jet fans running.

27. November: It is NO3 who gives start of 24 jet-fans. Dust monitor 2,3 and 4 is often above 200 µg/m^3. This indicates that we could have started fewer jet fans at an earlier time, and not have been forced to start 24 jet fans.
Figure 6 show us the NO distribution of 27. November, and Figure 7 the dust distribution the same day.

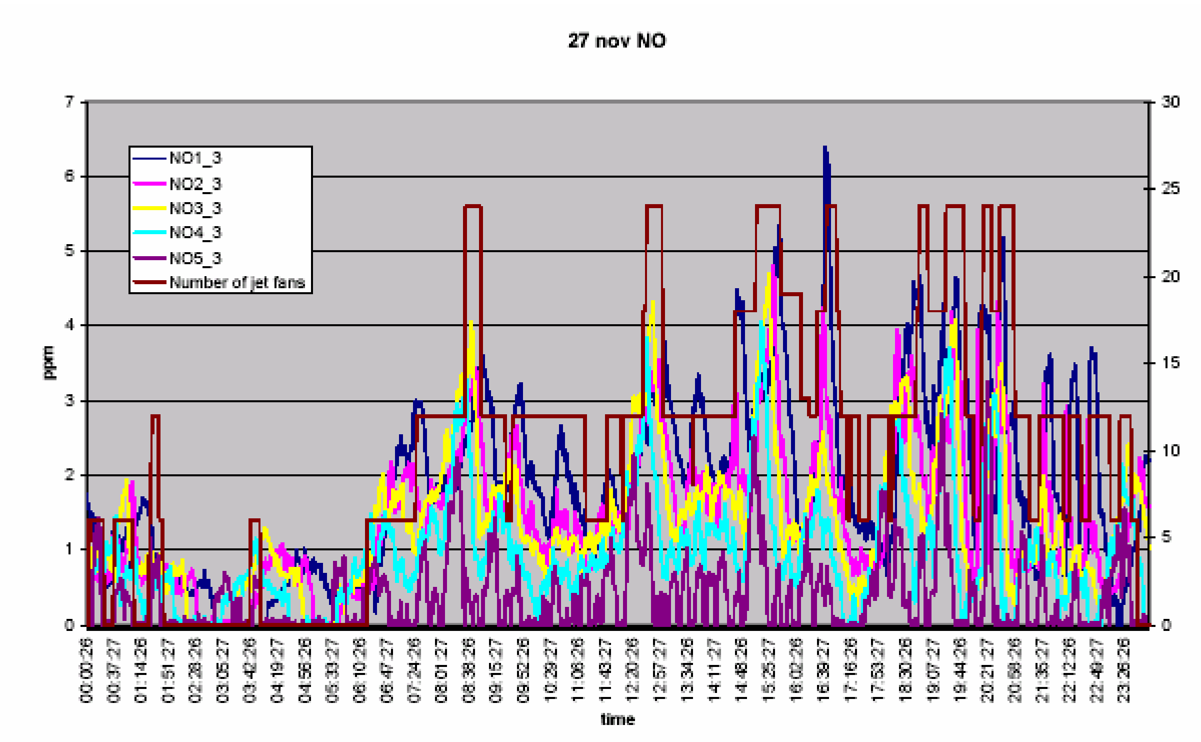


Figure 6

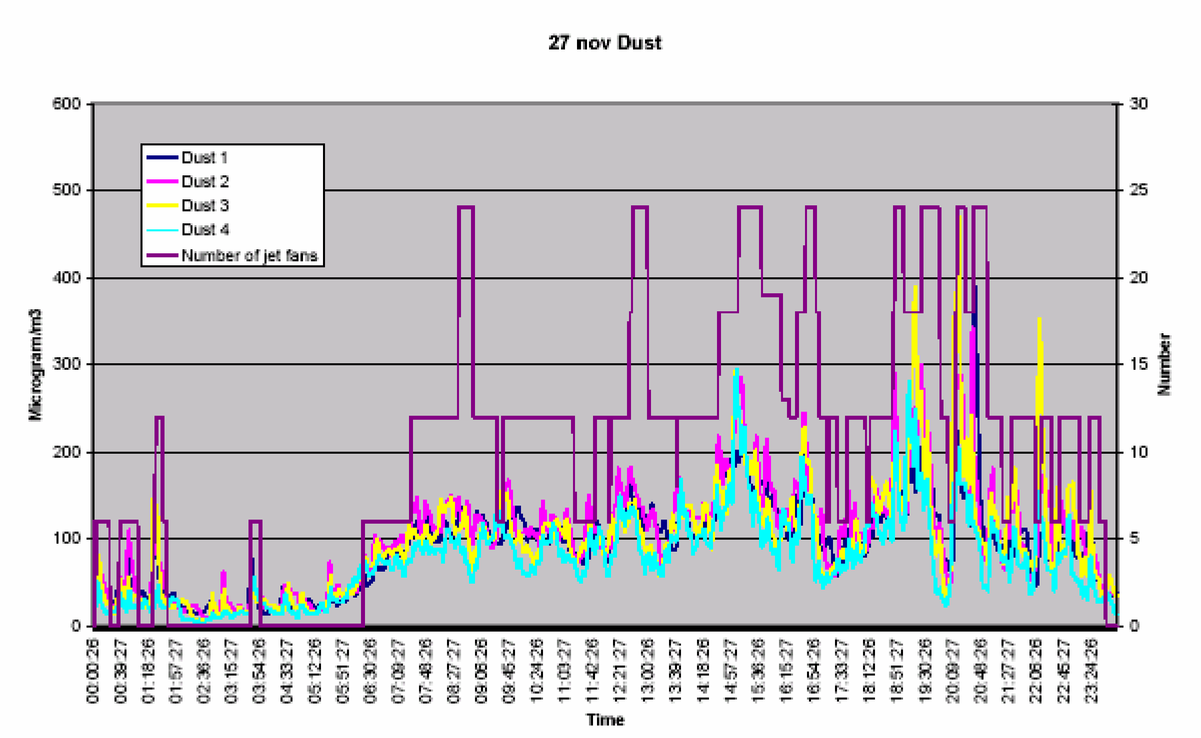


Figure 7

28. November: NO 1 and dust1 are changing between starting 24 jet fans.

29. November: Described earlier

30. November: 24 jet fans started by dust 1

1.December: NO 3 starts 24 jet fans.

2. December: NO 3 and dust 1 starts 24 jet fans once each.

Humidity and temperature in period 1:
Humidity: Relative humidity throughout the tunnel has been decreasing in the direction of ventilation. It has in this period never been visible humidity inside the tunnel.
Temperature and humidity conditions inside an outside the tunnel has not given any risk of fog inside the tunnel in period one.

During the time until the end of January 2002 the parameters for start of ventilation was changed several times, with the goal of finding the most optimal settings for acceptable air quality and low cost. One of the more surprising things we discovered was that we had a decrease in the number of complaints and a large reduction of cost for the final situation.

The final parameters before ending the test and analysis section was

Sensor	Unit	Main step 1	Main step 2	Main step 3	Main step 4
NO-1	ppm	7	12	15	30
Dust-1	µg/m3	300	2100	2000	2500
CO-1	ppm	50	100	150	200
NO-2	ppm	5	8	10	12
Dust-2	µg/m3	400	2100	2200	2500
CO-2	ppm	25	50	75	100
NO-3	ppm	4	7	10	13
Dust-3	µg/m3	400	2100	2200	2500
CO-3	ppm	25	50	75	100
NO-4	ppm	4	7	8	12
Dust-4	µg/m3	400	2100	2200	2500
CO-4	ppm	25	50	75	100
NO-5	ppm	3	7	10	12
CO-5	ppm	25	100	150	200

Smaller adjustments have been done later.

We will now look at the effect used in the tunnel for the different periods

If the dust concentrations rise above 700-800 mikrogram/m3 the number of complaints will increase (thy have reason to complain).

Special conditions.

23 januar dust monitor 1 goes high

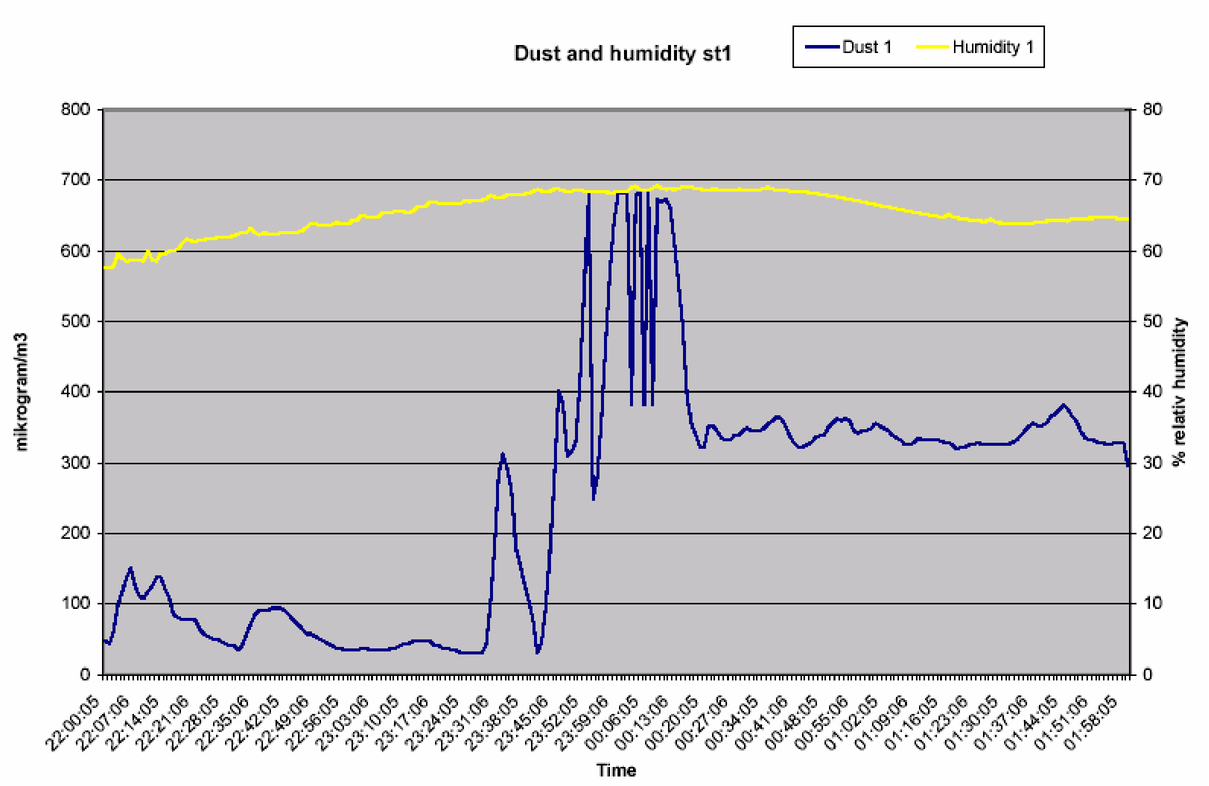
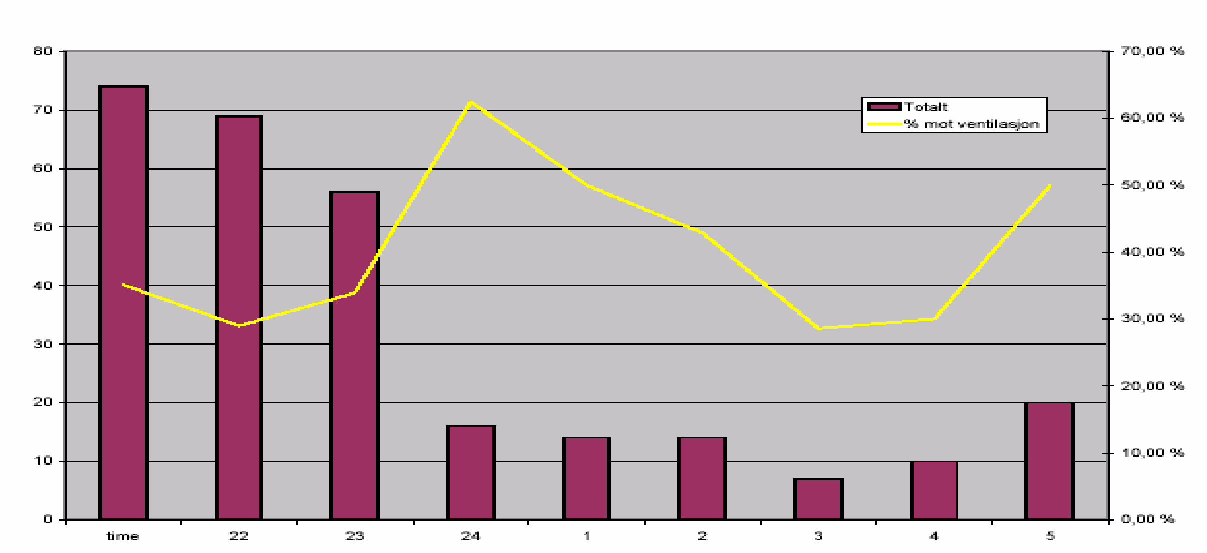


Figure 8 measured dust concentration and relative humidity at station 1

Figure 8 shows us the measured dust concentration at the time when we have a high measured dust concentration. At this time, CO and NO are low. Figure 9 shows us the traffic at the time. None of this gives us an explanation of these high levels of aerosols. To find an explanation for this high levels of aerosol it was necessary to go into the measured values on one timestamp. We are the lokking at the measured values at 23. January 23:46. The outside values are rH : 99.5% and Temperature : -6^{o}C, at measuring station one inside the tunnel we has rH: 68% an Temperature 0.7 ^{o}C. What happens when a truck enters an draw cold outside air in to the tunnel. The outside air is close to fog and cold. When the air inside the tunnel are cooled down to –6^{o}C this would give a rH > 100% which is impossible → fog. Since the main airflow is in the other direction, the fog will be temporary, and short timed after each truck, which is what we measured.



80
70
60
50
40
30
20
10
0
time
22
23
24
1
2
3
4
5
70,00 %
60,00 %
50,00 %
40,00 %
30,00 %
20,00 %
10,00 %
0,00 %
Totalt
% mot ventilasjon

Figure 9

6 februar 2002

Again we has a situation with abnormal high aerosol concentrations as show in Figure 10. Her we can se that the other aerosol measuring stations has lower peeks. This indicates a higher aerosol concentration than normal in the entire tunnel.

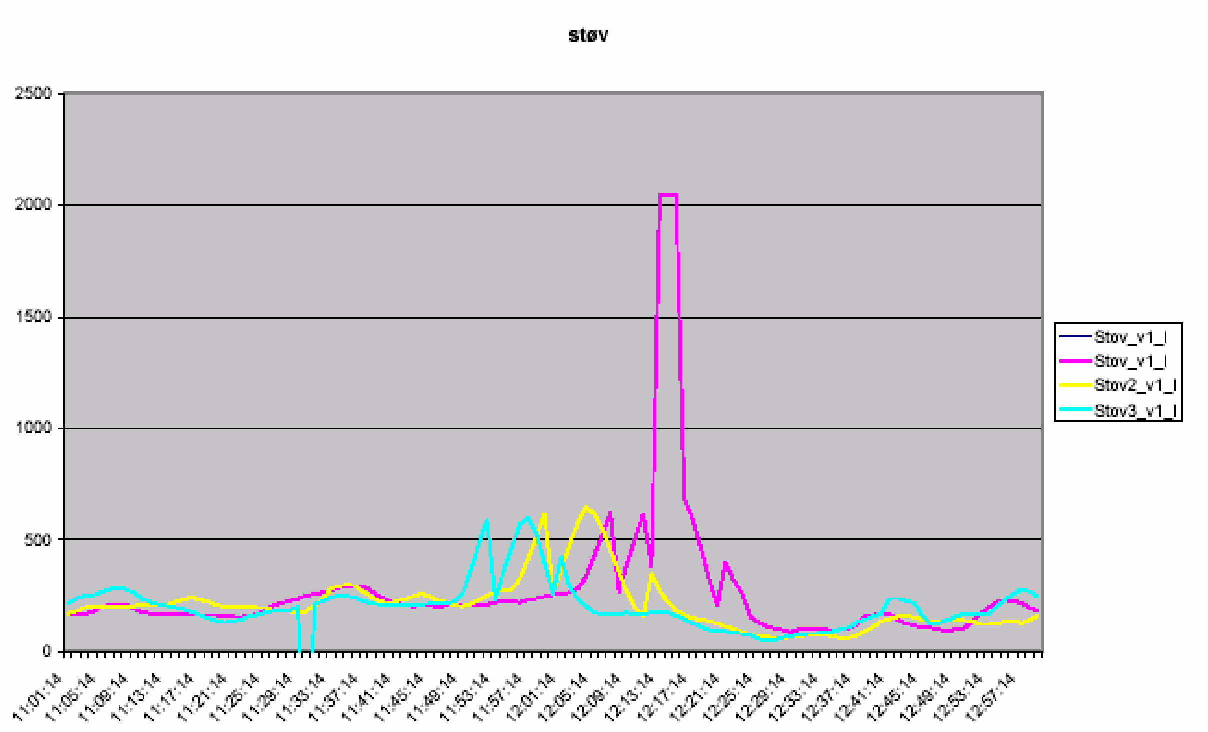


Figure 10

The same calculations as done for 23 january gives that we do not have the same problem. This time it is in fact high concentration of aerosols. If we looks at the wind speed in the tunnel, and the number of fans running, we discovers that we has a situation where we need 42 fans to keep a wind speed on 3m/s. This speed is normally given with 6 to 12 fans. It has also for large parts of the day been a diesel generator running in the tunnel. But the extreme levels, was probably caused by one or two trucks with badly adjusted engines. That a few badly adjusted heavy trucks can do this has been observed.

Overview of total effect used at the site.

	Maximum kW	
August	1635kW	
September	717 kW	
Oktober	707 kW	
1-19 november	1455 kW/h	19 of November effect control of the pumps was added to the control system. This causes the pumps to wait until it six 6 or less fans running.
20 nove-2 des	550 kW/h	
3 des- 13 des	535 kW	

2 Januar 2002 to 13 Januar 2002 max effekt 462 kW.

Average used kW/h each day for the different measuring periods are as follows.

from	to	kW/h pr day
18.6.2001	31.7.2001	7231
1.8.2001	25.8.2001	7306
27.8.2001	31.8.2001	8255
1.9.2001	30.9.2001	7321
1.10.2001	31.10.2001	7442
1.11.2002	2.11.2001	9427
5.11.2002	19.11.2002	7262
20.11.2001	2.12.2001	7517
3.12.2001	13.12.2001	8217
21.12.2001	1.1.2002	5699
2.1.2002	13.1.2002	6305

The period 21.12.2001 to 1.1.2002 is exceptionally low, but should not be counted since the traffic at this time is quite different from the rest of the year. Figure 11 show us the effect used for the fans in the different periods. The timeframe from 21.12.2001 to 1.1.2002 is specially low but should not be given a high credit due to the special traffic conditions around Christmas and new year. Other days that has been removed are days when we have changed the parameters for running the fans.

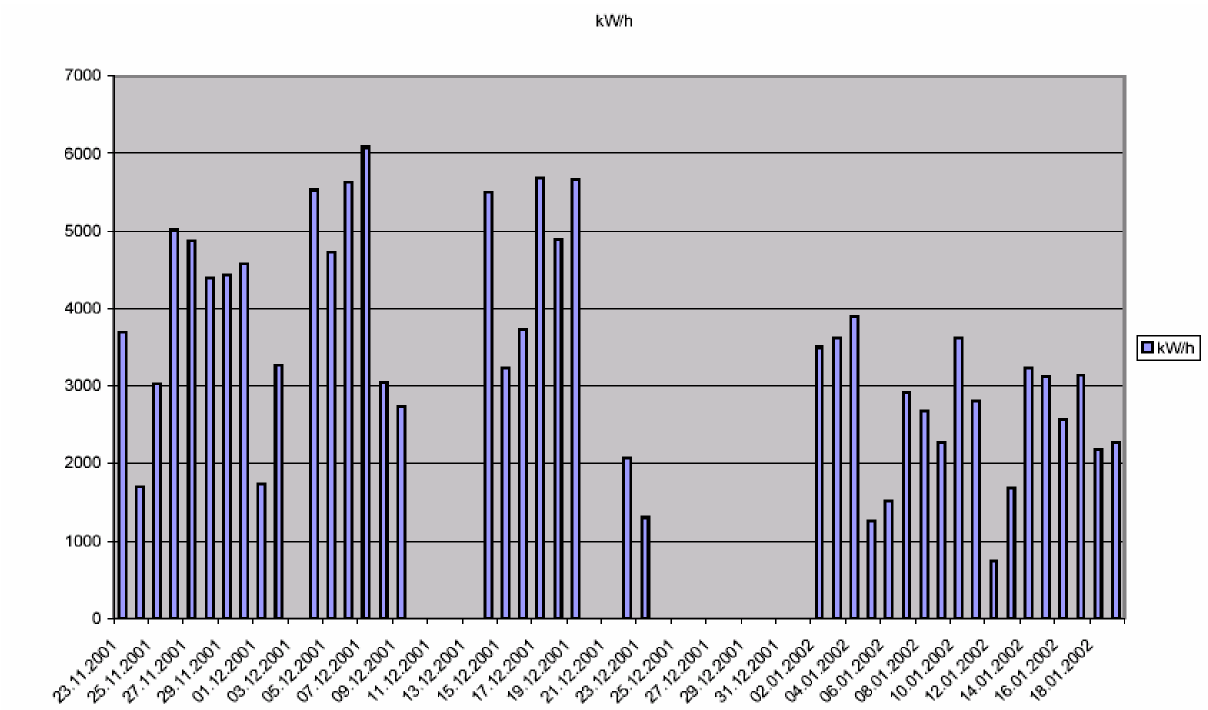


Figure 11 Effect used for the fans

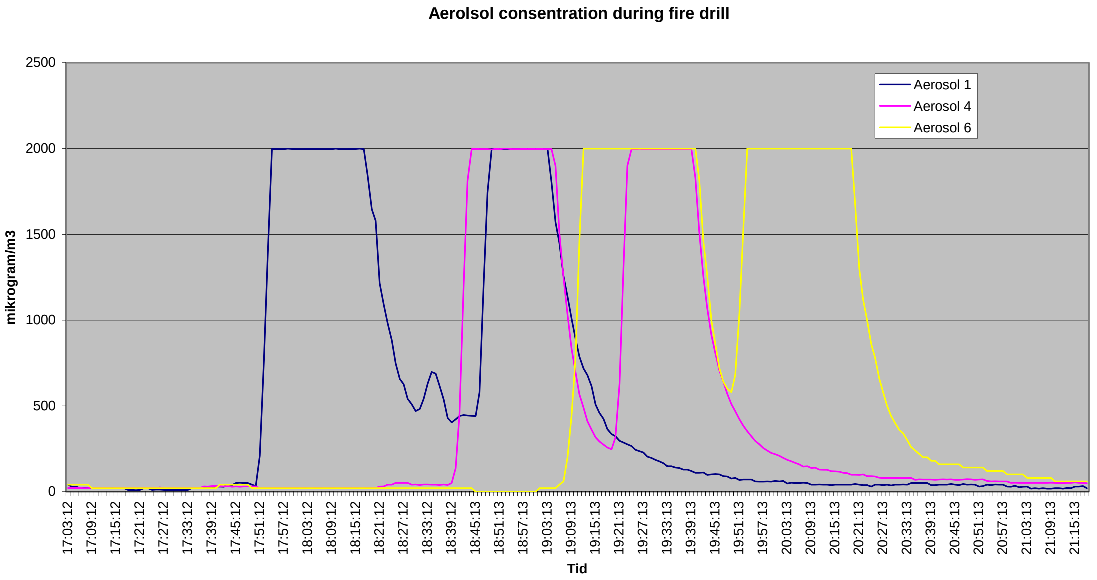
What is the difference between the actual measuring time frames?

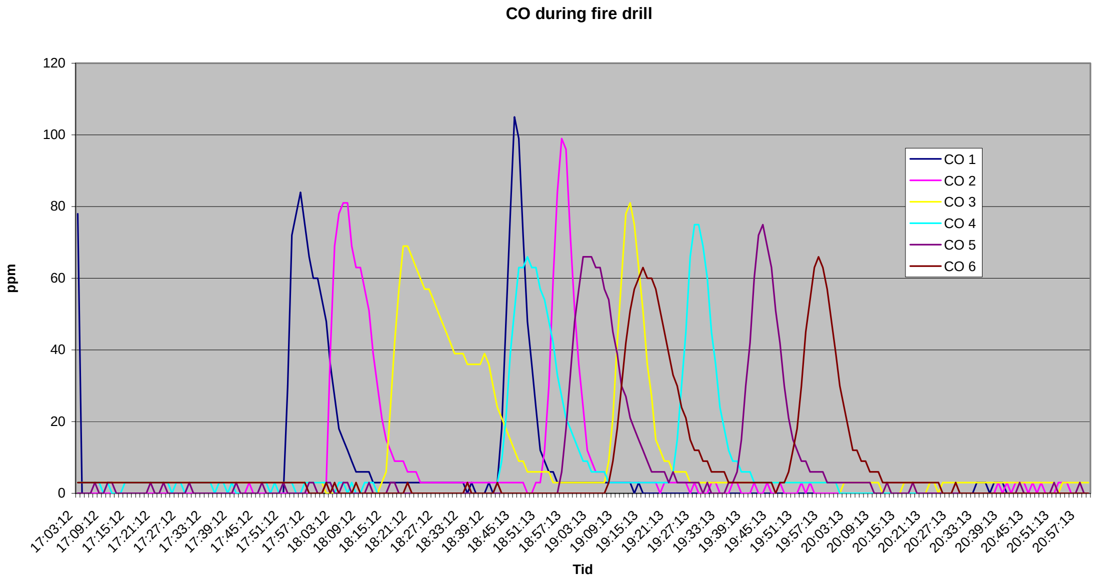
Until November 19 we only had one aerosol/dust monitor in the tunnel. (Dust 1)
Until August 26. we had a lot of complaints on air quality in the tunnel.
After august 27 we changed the parameters and the number of complaints was reduced, but still too high.
November 19. The installation of dust monitor 2,3 an 4 was completed together with measurement of temperature and relative humidity, and analysis of logged data for optimizing ventilation control could start.
Optimising of ventilation control gave us a decrease in used kW/h approximately of 1200 kW/h pr 24 hours, together with a decrease in highest our.

The Folgefonn tunnel

The Folgefonn tunnel is a ca 10800m long tunnel, with longitudinal ventilation, and very little traffic.
The only reason data from this tunnel is of interest are that we where logging in these tunnels during a fire drill. The drill's was including igniting an old car in each of the tunnels.

We will only give a short view of the logged values during and after the fire.





As can be seen from the logged values only aerosol measurement results in a value that indicates that the tunnel should close.

Kolltvedt tunnel

This is (in our terms) a high traffic tunnel wit bi-directional traffic. It is only 1070m long, but with traffic of 16500 vehicles a day

It was a tunnel where the software for the fan control never had worked properly. The introduction of flow measurement and aerosol measurement together with new software solved the problem. Here we were moving from a situation where a lot of drivers chose to drive around the tunnel, to a tunnel with acceptable air quality. This increased the use of energy for fans in the tunnel.

But the new equipment allowed us to optimise so we always started the fans in the direction of natural or traffic induced airflow. Attempts were made for fan control toward constant airflow, but this was futile in a tunnel this short.

But here we made the software so we could average continuously the measured NO_2, which resulted in a correlation on 0.92 (Only calculated for one day, 24/1-2003 aerosol toward NO_2 1. More calculation should be done before drawing conclusions)
The same calculation done for the period 17. jan 2003 to 26. jan 2003 gives a reduced correlation to 0.73.
Why this difference? The first days of this have very low levels of NO_2. Mainly zero, which reduces the calculatedly correlation

Correlations, mathematically.

Other scientist has proved that in urban areas we might have a correlation between NO_2 and aerosols on 0.94 or better.

If we do this kind of calculations on the Bømlafjord tunnel, you must remember that the logged values of aerosols are averaged in 255 seconds, and that it is this value that are logged. For NO and CO it is the value at the moment that are logged. This introduces an error.

Still with these errors we have a correlation on 0.7 for one week at measuring station one in the Bømlafjordtunnel. Of the other tunnels, which have a log, only the two short tunnels Hopstunnel and Nesttun tunnel (opened fir traffic 17. desember 2002) are logging NO with decimals.
The situation with averaging values is the same as in the Bømlafjordtunnel.

The correlation aerosol / NO are here 0.6. But the highest measured value of NO is 5,1 ppm, but 90% is below 2 ppm. Accuracy approximately 1 to 1.5 ppm

It is reason to believe that if scientific measuring equipment had been used for NO or NO_x measurement we would have obtained a far better correlation.

In effect the NO measuring in the tunnels that has aerosol measurement installed now is only for high alarm warning. Aerosol levels starts a few fans at an earlier time, so the max effect is reduced, resulting in reduced max effect cost.

References:

Ref 1	University of Minnesota: Review of particulate matter sampling methods supplemental report #2; aerosol dynamics, laboratory and on-road studies by: David B. Kittelson, Pd.D., Winthrop F. Watts,Jr., Ph.D. and Megan Arnold; July 1998
Ref 2	University of Bergen: Støvmålinger I Nygårdstunnlen by Walter Wedberg; pub LM376; 7 October 1999
Ref 3	University of Bergen; Thesis "Måling av sikt og turbiditet ved spreiing av infrarødt lys" by A. Tjugum from 1998
Ref 4	The Danish Air quality monitoring program. Annual report for 1998, NERI Technical report No. 296 bu Kåre kemp and Finn Palmgren